Predictive Calculation of the Arterial Gasometric Variables during the Transfer of Respiratory Patients by Air

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ABSTRACT

The latest recommendations published for the air transport of patients with respiratory pathology are those of the British Thoracic Society[1]. These guidelines describe the conditions required to allow their transport in commercial pressurized air lines. They present a management protocol for the patients based on the basal pulse oximetry at sea level, indicating those patients who will require supplementary oxygen, but without listing the specific contraindications to flying with the exception of current closed pneumothorax or active tuberculosis. A number of formulae exist that attempt to predict in-flight hypoxaemia but which, at the end of the day, have the same applicability as the protocol of the British Thoracic Society, concluding with the recommendation of whether or not to administer supplementary oxygen at two liters per minute, without individualizing the dose. In this article, our aim is to present a change in the current focus on the problem.

We propose an analysis of the clinical situation of the patient, performing arterial gasometry at ground level and calculating the alveolar-arterial oxygen gradient. Using these Data in the formula that we propose, we individualize the management of the patient during air travel, optimizing the air transport of cases of respiratory pathology.

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[1] British Thoracic Society Standards of Care Committee. Managing passengers with respiratory disease planning air travel: British Thoracic Society recommendations. *Thorax* 2002;57:0-15.

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This will avoid delay in the transfer of patients with acute respiratory pathology by ensuring a correct oxygen delivery and facilitating the early detection of complications. This is a group of particular importance in evacuations in the military environment, in both pressurized and non-pressurized transport.

In cases of chronic respiratory pathology, hyperoxia and the consequent retention of carbon dioxide, an ever-present risk in this population group, will be avoided. Their individualized management will make air transfer possible for a large group of patients for whom there currently exist general guidelines for supplementary oxygen delivery without quantifying this in an individualized manner and which can, therefore, lead to difficulties in the control of undesirable effects.

1. INTRODUCTION

In 2002, approximately 1000 million people used air travel throughout the world. It is estimated that this figure will increase in the short term.

Twenty-five years ago it was calculated that 5% of all passengers using commercial air travel had some form of pathology[2]. Given the current prevalence of the various pathologies, the better quality of outpatient control of chronic pathologies and the wider access to air travel, it would not be unreasonable to assume that the above datum by Iglesias et al. is still valid or has now increased.

The prevalence of chronic respiratory pathology in the Western world is currently estimated between 0.8 and 10%[3]. The incidence of acute respiratory failure is estimated between 109 and 137 cases/100,000 persons/year[4,5].

According to the latest recommendations of the British Thoracic Society for patients with respiratory pathology traveling by air, a hypoxaemia test in a hypobaric chamber is recommended for all passengers with pulse oximetry values of 92-95% at sea level and any of the following risk factors: hypercapnia, FEV_1 < 50% of the calculated value, lung cancer, restrictive parenchymatous pulmonary disease, restrictive alterations of the chest wall, restrictive lung pathology due to muscle disease, mechanical ventilation, cardiac or cerebrovascular disease. The result of this test will recommend whether or not supplementary oxygen should be administered during a flight in a generic manner at 2 l/min. The use of supplementary oxygen is indicated in all passengers with pulse oximeter readings of less than 92% without the need to perform the test in the hypobaric chamber. In those patients who require supplementary oxygen at sea level, an increase in the flow rate of oxygen during the flight at cruising level is indicated.

2. RESPIRATORY PHYSIOPATHOLOGY APPLIED TO AIR TRANSPORT

2.1. Respiratory physiology

The basic purpose of the respiratory apparatus is to ensure an adequate availability of oxygen, transported by the blood. The body adjusts the respiratory rate and volume (Tidal vol.) appropriately, depending on the mixture of gases being breathed.

2 Iglesias R, Cortes MDCG, Almanza C. Facing air passengers' medical problems while on board. Aerospace Med 1974;45:204-6.

3 Halbert RJ et al. Interpreting COPD prevalence estimates. What is the true burden of disease?. Chest 2003; 123: 1684-1692.

4 Luhr OR, Antonsen K, Karlsson M, Aardal S, Thorsteinsson A, Frostell CG, Bonde J. Incidence and mortality after acute respiratory failure and acute respiratory distress syndrome in Sweden, Denmark, and Iceland. The ARF Study Group. Division of Anaesthesia and Intensive Care, Karolinska Institute at Danderyd Hospital, Stockholm, Sweden. Am J Respir Crit Care Med 1999 Jun;159(6):1849-61.

5 Behrendt CE. Acute respiratory failure in the United States: incidence and 31-day survival. Children's Hospital, San Diego, CA, USA. Chest 2000 Oct;118(4):1100-5.

The final effector organ of gas exchange is the complex formed of the alveolus (exterior body surface), alveolar epithelium-alveolar basement membrane-interstitium-vascular endothelium (semipermeable membrane that separates the exterior surface of the body from the gas transporter), and the blood (transporting oxygen and other gases).

To define the functional status of our patient, we must take a number of factors into account, particularly in view of the possibility of changes in the barometric pressure (BP):

a. Gas solubility: this characteristic is intrinsic to each gas and varies with temperature and pressure. Under physiological conditions, the alveolar temperature will be the core temperature of the patient and the changes in pressure will depend on changes in the barometric pressure, affecting the partial pressures of each gas in the mixture.

b. Gas diffusion across the respiratory functional unit (alveolus-capillary): this will depend on the characteristics of the gas, the transmembrane gradient and the characteristics of the semipermeable membrane (the respiratory functional unit) that separates the mixture of gases from the blood.

A parameter exists, the alveolar-arterial oxygen gradient (Aa grad O_2), which expresses the gradient between the alveolar oxygen pressure (measure of the gas in the air being breathed) and the oxygen pressure in arterial blood when the blood interacts with this gas mixture across the alveolar membrane - interstitium- vascular endothelium. The result reflects the total of the millions of alveolar-arterial pulmonary effector functional units of gas exchange.

In the absence of clinical changes in the pulmonary functional situation of the patient, the Aa grad O_2 remains constant, independent of the inspiratory fraction of oxygen and, therefore, of atmospheric variations in the inspired air or the supplementary supply of oxygen. It is thus an optimal reference value for studying the status of the global respiratory functional unit and for the management of the patient during air transport.

2.2. Basal situation

The respiratory situation of any patient/passenger must be known prior to exposure to a hypobaric environment.

Respiratory insufficiency is usually defined as that clinical situation in which the partial pressure of oxygen in arterial blood (PaO_2) is less than 60 mmHg.

Basically, the patients with respiratory insufficiency are divided into two groups: carbon dioxide retainers and non-retainers. This separation is due to the different behavior that these patients present when faced with an increase in the partial pressure of oxygen in inspired air that corrects the hypoxia due to the respiratory failure.

To determine the in-flight management of all these cases, we introduce a parameter that reflects the functional status of each patient's alveoli-capillary barrier, the final effector organ of gas exchange. This parameter is the Aa grad O_2, as described above.

The Aa grad O_2 is defined as the difference between the alveolar oxygen pressure and the arterial oxygen pressure. The alveolar oxygen pressure is determined by the composition of the mixture of atmospheric gases at 100% water saturation. The arterial oxygen pressure is measured by arterial gasometry.

The composition of the mixtures of the different respiratory gases is shown in table 1

Table 1: Composition of the mixtures of respiratory gases.

	Mixture of inspiratory gases (atmospheric)	Mixture of inspiratory gases (alveolus)	Mixture of expiratory gases	Comments
Oxygen	0,21·(BP – PpH_2O)	0,21·(BP – 0,061 BP)	0,21·(BP – 0,061 BP)	BP varies according to altitude. PpH_2O varies according to the saturation of the atmospheric air
H2O	α · $SatH_2O$ · BP	0,061 · BP *	0,061 · BP	α at 37ºC = 6,1%
CO2	0,03%	0,03%	+/- Pa CO_2	
Nitrogen	PpN_2 = BP – PpO_2 – PpH_2O – $PpCO_2$ – Pp others	PpN_2 = BP – PpO_2 – PpH_2O – $PpCO_2$ – Pp others	PpN_2 = BP – PpO_2 – PpH_2O – $PpCO_2$ – Pp others	The partial pressure of nitrogen is defined by the displacement that it undergoes in the presence of other gases.
Others: argon, etc.	Maximum 1% (including CO_2)			

α: maximum water vapor carrying capacity of air at ambient temperature.

BP: barometric pressure (BP = P0 · $e^{-Mgh/RT}$). **Pp**: partial pressure (according to Dalton's law, the pressure of a mixture of gases is equal to the sum of the partial pressures of the gases that make up the mixture).

* In the alveolus, the water vapor pressure of the alveolar gas is 100%, forming 6.1% of the total mixture of gases at 37ºC.

2.3. Hypobaric environment

Air travel presents certain characteristics common to other forms of transport, such as movement, acceleration and deceleration, both antero-posterior and vertical, and the visual and auditory stimuli. None of these variables significantly effects respiratory function if they remain within the limits of commercial aviation or tactical military transport.

Having described the behavior of the mixture of gases in a medium with a constant BP, we must analyze the changes that occur in the data presented in table 1 on varying the BP according to altitude in a hypobaric situation such as air transport.

In table 2, the changes in the partial pressures of the gases according to altitude may be seen. It should be noted that the cabin pressure in commercial aircraft presents significant variability[6]. This is not a determining factor in the military flights, but must be known for the planning of health transport, as we are attempting to demonstrate in this article.

[6] Cottrell JJ. Altitude exposures during aircraft flight. *Chest* 1988;92:81-4.

Table 2: Partial pressure of the respiratory gases at the alveolar level according to barometric pressure, at 37 ºC and 100% humidity.

	0 meters = 0 feet (sea level)	**2438 meters = 8000 feet (+/- Bogota)**	**2743 meters = 9000 feet (cabin pressure)**
Oxygen	154,8 mmHg	115,0 mmHg	110,6 mmHg
H_2O	22,8 mmHg	16,9 mmHg	16,3 mmHg
CO_2 and others	< 7,6 mmHg	< 5,6 mmHg	< 5,4 mmHg
Nitrogen	574 mmHg	427,0 mmHg	411,0 mmHg
BP	760 mmHg	564,59 mmHg	543,33 mmHg

When arterial hypoxaemia develops in a traveler in a hypobaric environment, a series of compensatory mechanisms are brought into effect. Initially there is an increase in the respiratory volume by making use of the reserve inspiratory volume and increasing the respiratory rate. This can be resolved by the supply of supplementary oxygen, stabilizing the PaO_2.

The provision of supplementary oxygen will prevent respiratory fatigue by avoiding hyperventilation and bathypnea. However, these measures carry two risks:

a. Under-evaluation of an exacerbation of the patient’s respiratory disorder; the excessive supply of oxygen may mask acute changes, impeding early detection and thus leading to the late diagnosis of complications.

b. A second risk, even more frequent, is the excessive supply of oxygen to the chronic patient, blocking the hypoxaemic ventilatory stimulus with the consequent hypoventilation and carbon dioxide retention.

We shall attempt to avoid these risks by calculating precisely the oxygen requirements in a hypobaric environment according to the respiratory pathology (acute or chronic) presented by the patient.

3. CALCULATION OF THE IN-FLIGHT INSPIRATORY OXYGEN FRACTION REQUIREMENT

3.1 Formula proposed

The proposal made here is to determine the appropriate in-flight FiO_2 using the formula presented below. The formula is derived from the re-ordered analysis of the variables that determine the patient's basal Aa grad O_2, which will be applied as a constant in the calculation of the in-flight FiO_2. This FiO_2 will be re-calculated in the event of any change in the in-flight BP (which is a known parameter) in order to achieve the target PaO_2 for the patient. The derivation of the formula is presented in table 3.

Table 3. Development of the formula for in-flight oxygen prescription.

$Aa\ grad\ O_2 = FiO_2\ (BP - PH_2O) - (PaCO_2/0{,}8) - PaO_2$.

We obtain:

- Patient's Aa grad O_2 (basal, stable pathology)
- $PaCO_2$ (basal gasometry)

We calculate:

- Target PaO_2 for the patient

⇓

Basal Aa grad O_2 = FiO_2 (In-flight BP– PH_2O) – (Basal $PaCO_2$ /0,8) – Target PaO_2

⇓

$$\boxed{FiO_2 = \frac{\text{Basal Aa grad } O_2 + \text{Target } PaO_2 + (\text{Basal } PaCO_2 / 0{,}8)}{\text{In-flight BP} - 0{,}061 \cdot \text{In-flight BP}}}$$

The first step is to perform an arterial gasometry on the patient, calculating the Aa grad O2 from a known BP and inspiratory fraction of oxygen.

From this moment on, 3 fundamental data are used: a known Aa grad O2, a known arterial CO_2 pressure (from the gasometry performed), and the patient's clinical profile (acute or chronic respiratory pathology).

The following step is to establish the in-flight inspiratory fraction of oxygen. For this purpose it is necessary to know the planned BP at cruising altitude in the flight to be undertaken. Secondly, the desired PaO_2 (target PaO_2), which differs according to whether the patient has acute or chronic pathology, must be taken into account.

Finally, the proposed formula is applied to obtain a rapid calculation of the inspiratory fraction of oxygen.

3.2. Acute respiratory pathology

In patients with acute respiratory pathology, the aim is to avoid hypoxaemia and maintain respiratory stability in the patient by avoiding both the use of the reserve inspiratory volume and tachypnoea, thus ensuring patient comfort.

A fundamental aspect is the choice of the target PaO_2. If the target PaO_2 is too close to the lower limit, e.g. PaO_2 = 60 mmHg, a small variation in the planned cabin pressure may cause the patient to hyperventilate, increasing respiratory work. If the target PaO_2 is too high, e.g. PaO_2 = 85 mmHg, the excessive supply of oxygen may lead to possible changes in the patient's respiratory situation going undetected and not becoming evident until the compensatory mechanisms are overburdened.

A reasonable target PaO_2, with a good safety margin, would be a PaO_2 of 65-70 mmHg.

3.3 Chronic respiratory pathology

The objectives in patients with chronic respiratory pathology are two fold. The first is to avoid clinical hypoxaemia and avoid the recruitment of compensatory mechanisms that are chronically exhausted or almost exhausted. The second objective is to avoid hyperoxemia that would inhibit the hypoxic reflex that maintains the respiratory stimulus in these patients.

The target partial pressure of oxygen must be 60 mmHg or, in some patients on chronic treatment with domiciliary oxygen, even lower, e.g. PaO_2 = 55 mmHg.

An example of the in-flight oxygen prescription to manage both patient profiles is given in the following table (table 4).

Table 4: In-flight oxygen prescription according to acute or chronic respiratory pathology, alveolar-arterial gradient of the patient and cabin pressure.

		Acute profile			Chronic profile		
Cabin pressure	Basal Aa grad O_2	$PaCO_2$	Target PaO_2	**Indicated FiO_2**	$PaCO_2$	Target PaO_2	**Indicated FiO_2**
760 mmHg = 0 meters = 0 feet	30	40	65	**0,21**	50	60	**0,21**
	60	40	65	**0,24**	50	60	**0,26**
	90	40	65	**0,29**	50	60	**0,30**
681,15 mmHg = 914 meters = 3000 feet	30	40	65	**0,23**	50	60	**0,24**
	60	40	65	**0,27**	50	60	**0,28**
	90	40	65	**0,32**	50	60	**0,33**
609,09 mmHg = 1828 meters = 6000 feet	30	40	65	**0,25**	50	60	**0,27**
	60	40	65	**0,31**	50	60	**0,32**
	90	40	65	**0,36**	50	60	**0,37**
543,33 mmHg = 2743 meters = 9000 feet	30	40	65	**0,28**	50	60	**0,30**
	60	40	65	**0,34**	50	60	**0,36**
	90	40	65	**0,40**	50	60	**0,42**

4. CONCLUSIONS

We believe that the proposed method for the calculation of the inspiratory fraction of oxygen in patients with respiratory pathology will facilitate the medical management of these patients during air travel. First, it allows us to establish in-flight therapeutic safety objectives in patients with altered respiratory function. Secondly, the onset of desaturation during the flight will give us an early warning of the onset of new respiratory events on top of the patient's basal pathology, enabling rapid action to be taken. Finally, it enables the safe transport of patients in extreme situations, e.g. patients with advanced pathology or the performing of health transport in non-pressurized flights.

During transfers within the military environment, the use of non-pressurized air transport gives rise to a variability in the BP that can only be partially controlled. The need to maintain a certain flying altitude or on missions undertaken in territory at high altitude means that the BP may be a determining factor of the patient's clinical situation. In this situation, the application of the formula using the minimum BP according to the planned flying altitude will allow us to avoid desaturation.

Secondly, high altitude, pressurized, long haul transport (transcontinental) in the repatriation of patients must be undertaken with the greatest possible safety. This most frequently involves patients with acute respiratory pathology. Some of them, due to the time course of their pathology in the area of operations, may behave as chronic patients. Long haul transfers must be correctly planned and the application of the

formula will enable the appropriate use of equipment, the correct prescription of oxygen, the prevention of complications (in patients with a chronic profile) and the early detection of respiratory complications (desaturation in patients with an acute profile). Given the complexity of these repatriation operations, we believe that facilitating the determination of respiratory requirements will simplify one of the fundamental variables in the management of these patients.